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SIMPLIFIED APPROACH FOR THE LONG-TERM BEHAVIOUR OF TIMBER-CONCRETE COMPOSITE BEAMS ACCORDING TO THE EUROCODE 5 PROVISIONS

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Simplified approach for the long-term behaviour of timber-concrete composite beams according to the Eurocode 5 provisions

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1 Introduction

The timber-concrete composite beam (TCC) is a construction technique extensively used for both upgrading of existing floors and new buildings. Many advantages can be achieved by connecting a lower timber beam with an upper concrete slab, including increase in strength and stiffness, better seismic performance, larger thermal mass and fire resistance, better acustic separation, and the possibility to maintain the timber floor when restoring existing buildings (Ceccotti 1995).

The design of the TCC must satisfy both ultimate (ULS) and serviceability (SLS) limit states (CEN 2003). The former are controlled by evaluating the maximum stresses in the component materials (concrete, timber and connection system) using an elastic analysis (Ceccotti 1995). Such approaches generally lead to solutions sufficiently accurate provided that realistic properties of the connection system are employed (Ceccotti et al. 2006).

The SLS are checked by evaluating the maximum deflection both in the short- and long-term. Timber, concrete and connection systems, in fact, all show time-dependent behaviour. Concrete is characterised by creep, shrinkage and thermal strains; timber exhibits creep, mechano-sorptive creep, which is the increase in delayed strains due to cycles of moisture content, shrinkage/swelling, and thermal strains; the connection system itself is also characterised by creep and mechano-soprtive creep. This results in the long-term behaviour being affected also by the environmental conditions. Some numerical models have been proposed in order to evaluate rigorous solutions (Fragiacomo 2005, Schänzlin 2003). The former FE model was compared against a number of long-term experimental tests (Fragiacomo and Ceccotti 2006) showing the possibility to predict accurate results. The software accounts for all of the aforementioned time-dependent phenomena using the Toratti's rheological model (Toratti 1992) for the creep and mechano-sorptive creep of timber and connections system, and the CEB-FIP Model Code 1990 formulas (CEB 1993) for the creep and shrinkage of concrete. The actual distribution of moisture content, which was proved to be highly variable over the timber cross-section (Fragiacomo and Ceccotti 2006), is computed by solving the diffusion problem for a given history of environmental relative humidity. The temperature distribution, much less variable, is instead considered as constant over the cross-section but variable in time.

A simplified analytical approach was also proposed (Ceccotti 1995), however further research highlighted that some phenomena ignored in such an approach such as concrete shrinkage and inelastic strains due to environmental conditions may lead to significant errors and make the simplified solution not conservative (Ceccotti et al. 2006, Fragiacomo 2006, Fragiacomo et al. 2006a). Some more accurate methods for the long-term behaviour have then been proposed. Kuhlmann and Schänzlin (2003) proposed the use of effective values of creep and shrinkage to take into account the different trends in time of those coefficients in the component materials (timber, concrete and connection system). Fragiacomo (2006) proposed an improvement of the Ceccotti's approach in order to account for the mechano-soprtive creep, concrete shrinkage, and inelastic strains/stresses due to environmental temperature and relative humidity variations.

The aim of this paper is to propose a simplified yet accurate solution for the long-term behaviour of TCC's. The approach will allow the designer to account for the whole loading history of the structure including concrete shrinkage, effect of props during construction, and inelastic strains due to environmental variations. The accuracy will be assessed by comparison with numerical solutions on a number of TCC's of technical interest. Finally the influence of different environmental conditions such as outdoor and heated indoor conditions on the long-term performance will be discussed.

2 Prediction of the long-term behaviour of TCC's

2.1 Current approach

The current approach proposed by Ceccotti (1995) superimposes the effects in time of the dead and live loads applied on the TCC. Let g_1, g_2 and $\psi_2 q$ be the self weight of the TCC, the other part of the dead load, and the quasi-permanent part of the live load q (ψ_2 is equal to 0.3 for domestic and office floors) respectively. t_1, t_2 and t_3 are the times when the loads are applied (t_1 is the time when the props are removed from the TCC) measured from the concrete pouring. A generic effect S (S may signify the deflection, the shear force in the connection system, the stress in the concrete or timber beam) at the time t can be evaluated by superimposing the effects of the different loads:

$$S = S(g_1) + S(g_2) + S(\psi_2 q) \tag{1}$$

where the effect of each load $S(g_i)$ is calculated using the formulas for composite beams with flexible connection suggested by the Annex B of the Eurocode 5-Part 1-1 (EC5) (CEN 2003). The global creep behaviour is taken into account by replacing the elastic E_j (j=c,t) and slip moduli K_{ser} with the effective moduli $E_{j,eff}(t)$ and $K_{eff}(t)$ in the EC5 formulas:

$$E_{c,eff}(t) = \frac{E_c(t_i)}{1+\phi_c(t,t_i)} \qquad E_{t,eff}(t) = \frac{E_t}{1+\phi_t(t-t_i)} \qquad K_{eff}(t) = \frac{K_{ser}}{1+\phi_f(t-t_i)} \qquad (2)\ (3)\ (4)$$

where ϕ_j are the creep coefficients of concrete (subscript c), timber (t) and connection system (f). The trend in time of the concrete creep coefficient ϕ_c and Young's modulus E_c can be calculated using the CEB formulas (CEB 1993). For timber, the current version of the EC5 suggests the final value (for t–t_i=50 years) of the creep coefficient ϕ_t, which is denoted with k_{def}, for different service classes. The trend in time (Fig. 1) can be obtained by interpolation of the values for different load duration classes (that is the quantity t–t_i) reported in an earlier (1995) version of the EC5. For the connection, the EC5 suggests that a creep coefficients twice as large as the timber one is adopted.

2.2 Proposed approach

The main advantage of the current approach is the simplicity, being based on closed form solutions. However a number of approximations are made, which were found to lead in some cases to significant errors (Fragiacomo 2006). The mechano-soprtive effect is not explicitely considered since there is no direct dependence of the creep coefficient upon the history of moisture content. An indirect allowance for the global time-dependent behaviour (creep and mechano-sorptive creep) is done by making the final creep coefficient dependent upon the service class. Some other phenomena are ignored, such as the concrete shrinkage, and the variation of temperature and relative humidity of the environment. Moisture content variations in timber and environmental temperature variations cause eigenstresses into the TCC. The proposed approach aims at improving the current approach by accounting for the aforementioned phenomena.

2.2.1 Dependence of the creep coefficient on the moisture content

The explicit dependence of the creep coefficient on the timber moisture content is assumed according to the Toratti's model (1992). For a piecewise linear history of moisture content with amplitude Δu [%] and period Δt, the creep coefficient of timber is given by:

$$\phi_t\left(t-t_i\right)=\phi_{tc}\left(t-t_i\right)+\phi_{tms}\left(t-t_i\right)=\left(\frac{t-t_i}{t_d}\right)^m+\phi^\infty\left[1-e^{-c\frac{2\Delta u}{100\Delta t}\left(t-t_i\right)}\right] \tag{5}$$

where ϕ_{tc}, ϕ_{tms} are the creep part and the mechano-sorptive part of the total creep coefficient of timber, t_d, m, ϕ^∞ and c are material parameters assumed equal to 29500 days, 0.21, 0.7 and 2.5, respectively. The moisture content distribution $u=u(P,t)$ is not constant over the timber cross-section but highly dependent upon the location of the point P. Furthermore, also the variation over time of the moisture content, which is influenced by the history of environmental relative humidity $RH=RH(t)$, is different over the timber cross-section. In order to simplify the problem, reference is made on the history of average moisture content $u_{aver}=u_{aver}(t)$, which is assumed to be uniform in each point P of the timber cross-section. Such a history is then approximated by a piecewise linear curve on a yearly scale, where $\Delta u=u_{aver,max}-u_{aver,min}$ represents the yearly fluctuation, and Δt=365 days. Eq. (5) is hence substituted into eq. (3) and (4) to account for the mechano-sorptive effect.

The comparison among the creep coefficients suggested by the EC5 for the different service classes and the creep coefficients evaluated according to the Toratti's model is reported in Fig. 1. It can be observed that the yearly variation of moisture content affects the rate of increase in time of the creep coefficient in the Toratti's model. However, the final value is independent of Δu for amplitudes larger than 1.65% (which is the case of technical interest), and is slightly lower than the value suggested by the EC5 for the 3rd service class. For no moisture content variations (Δu=0), the Toratti's model leads to a final value slightly higher than the EC5 final value for the 2nd service class, which may be considered as representative of an environmental condition with no significant moisture content variations and, therefore, no mechano-sorptive effect. Fig. 2 reports the comparison among the creep coefficients of timber, the creep coefficients of connection evaluated by doubling the creep coefficients of timber, and the values obtained by extrapolating the outcomes of an experimental test recently performed on the Tecnaria shear stud connection (Fragiacomo et al. 2006b). The figure points out that the creep coefficients suggested by the EC5 are far too large compared with the experimental values. When the outcomes of long-term experimental tests are not available, a more reasonable assumption for the connection creep coefficient seems to be the value of the creep coefficient of timber: $\phi_f = \phi_t$. This outcome is confirmed also by other experimental tests performed on glued rebar (Bonamini et al. 1990) and notched (Kuhlmann and Michelfelder 2004) connections. However, to be consistent with the provisions of the EC5, the assumption $\phi_f = 2\phi_t$ will be made in all analyses carried out in the following.

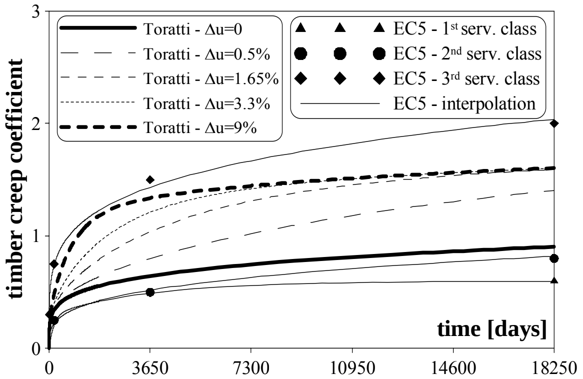

Fig. 1: creep coefficients of timber

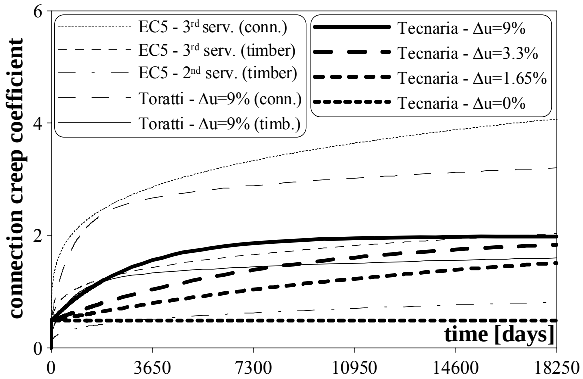

Fig. 2: creep coefficients of connection

2.2.2 Effect of concrete shrinkage

The effect of concrete shrinkage, ε_{cs}, is accounted for by using the closed form solutions for simply supported TCC's with flexible connections subjected to inelastic strains reported in Appendix (Fragiacomo 2006). In such formulas, the following substitutions are made:

$$\Delta\varepsilon_n = -\Delta\varepsilon_{n,c} = -\varepsilon_{cs}(t) + \varepsilon_{cs}(t_s) \qquad E_{c,eff}(t) = \frac{E_c(t)}{1+\phi_c(t,t_s)} \qquad (6)\,(7)$$

where ε_{cs} (<0) signifies the concrete shrinkage, which can be evaluated according to the CEB formulas (CEB 1993), and t_s signifies the time of concrete curing (usually 1 to 7 days after the pouring), when concrete begins shrinking. The influence of concrete, timber and connection creep is taken into account using the effective modulus method (eq. (7) for concrete, and eqs. (3)-(4) for timber and connections, with $t_i = t_s$ and ϕ_t, ϕ_f given by eq. (5)). It is interesting to point out that the construction type (propped or unpropped) does not markedly influence the effect of the concrete shrinkage on the TCC. Figures 3 and 4 report

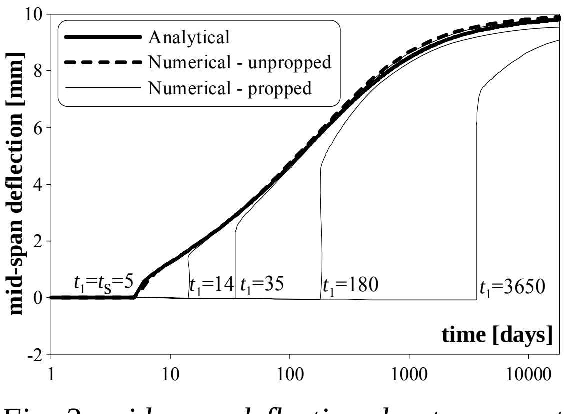

Fig. 3: mid-span deflection due to concrete shrinkage only

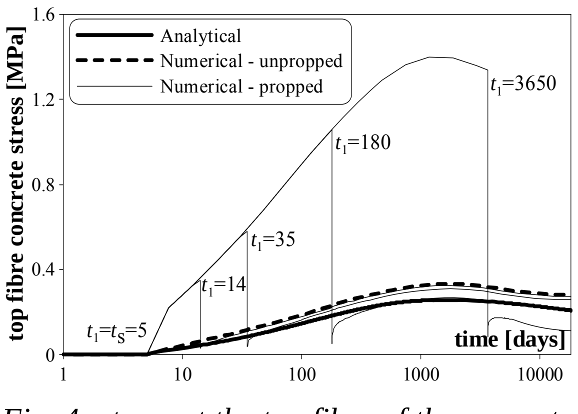

Fig. 4: stress at the top fibre of the concrete slab due to concrete shrinkage only

the trends in time of the mid-span deflection and concrete stress in the top fibre for the Florence TCC (see Table 1) subjected to concrete shrinkage only. The approximate curve carried out using the proposed method is compared against the curves obtained using a rigorous finite element program (Fragiacomo 2005). The mechano-sorptive effect has been neglected in this example. It can be observed that for any time of prop removal t_1, the numerical curve of the propped construction approaches the curve of the unpropped beam, which is well approximated by the analytical curve. The proposed approximate solution for concrete shrinkage can hence be used to evaluate any effect $S(t)$ for $t \geq t_1$.

2.2.3 Effect of shrinkage/swelling due to environmental variations

Environmental variations of relative humidity and temperature with respect to the values at the time of concrete curing t_s cause eigenstresses and deflection in the TCC. The variations of relative humidity $RH=RH(t)$ lead to changes in moisture content $\Delta u=\Delta u(P,t)$ with different amplitudes over the timber cross-section. The corresponding inelastic strains are evaluated with reference to the piecewise-linear curves approximating the yearly fluctuations of the moisture content averaged over the timber cross-section, $u_{aver}(t)$-$u_{aver}(t_s)$. The variation of environmental temperature leads to eigenstresses and inelastic strains in the TCC because of the different thermal expansion coefficients of timber and concrete. It was demonstrated (Fragiacomo and Ceccotti 2006) that the yearly variations of temperature in concrete and timber are almost the same as the environmental ones: $\Delta T_{c,y}=\Delta T_{t,y}=T_{y,max}-T_{y,min}$. Day-to-night variations are the same amplitude as the environmental ones for concrete: $\Delta T_{c,d}=\Delta T_d$, while for timber a reduction factor k should be applied, the amount of which depends on the size of the cross-section (k=0.8 for beams with breadth b_t=125 mm, k=1 for narrow joists with breadth b_t=38 mm): $\Delta T_{t,d}=k\Delta T_d$. The inelastic strains are evaluated with reference to a piecewise-linear curve approximating the yearly trend of the environmental temperature, $T(t)$-$T(t_s)$, and to the day-to-night variations, ΔT_d. The effect of yearly, $\Delta\varepsilon_y$, and daily environmental variations, $\Delta\varepsilon_d$, is accounted for using the elastic solution reported in Appendix with the following substitutions:

$$\Delta\varepsilon_n = \Delta\varepsilon_y = \alpha_{t,u}\left[u_{aver}(t) - u_{aver}(t_s)\right] + \alpha_{t,T}\left[T(t) - T(t_s)\right] - \alpha_{c,T}\left[T(t) - T(t_s)\right] \quad (8)$$

$$\Delta\varepsilon_n = \Delta\varepsilon_d = \alpha_{t,T} k \Delta T_d - \alpha_{c,T}\Delta T_d \quad (9)$$

Since the inelastic strains change in time with cyclic trend, the effect of creep and mechano-sorptive creep is negligible, therefore the Young's moduli of concrete, $E_c(t)$, timber, E_t, and connection, K_{ser} are employed in the formulas.

2.3.4 Superposition

The solution S of the TCC at a generic time t according to the proposed approach is carried out by superimposing the effects of the different loading conditions:

$$S = S(g_1) + S(g_2) + S(\psi_2 q) + S(\varepsilon_{cs}) + S(\Delta\varepsilon_y) + S(\Delta\varepsilon_d) \quad (10)$$

where the effects of creep and mechano-sorptive creep are taken into account on the solutions $S(g_1)$, $S(g_2)$, $S(\psi_2 q)$ and $S(\varepsilon_{cs})$ using the effective modulus method (eqs. (2)-(4) and (7)) and the Toratti's model (eq. (5)).

2.4 Numerical-analytical comparison

The accuracy of the proposed (eq. (10)) and current (eq. (1)) approach is assessed against the rigorous numerical solutions carried out using a FE model purposely developed (Fragiacomo 2005). Four TCC's are analysed: the 'Florence' beam, a long-span composite beam with glued rebar connection and deep glulam beam (Capretti and Ceccotti 1996); the

'Padua' beam, a medium-span composite beam with glued rebar connection typical of upgrading of ancient wooden floors (Turrini and Piazza 1983); the 'Cardington' beam, a short-span beam with narrow timber joists and inclined SFS screws representative of a possible upgrading of a domestic wooden floor (Grantham et al. 2004); the 'Fort Collins' beam, a short-span wood-concrete composite floor/deck system with shear/key anchor connection detail (Fragiacomo et al. 2006a). Geometrical and mechanical properties of the beams are summarized in Table 1 (see the Appendix for the meaning of the symbols).

Table 1: Geometrical and mechanical properties of the beams analysed

	Florence	Padua	Carding.	Fort Coll.		Florence	Padua	Carding.	Fort Coll.
g_1 [kN/m]	2.34	1.65	0.86	0.404	A_s [mm^2]	94	57	85	158
g_2 [kN/m]	0.6	0.6	0.36	0.114	t [mm]	50	25	15	0
$\psi_2 q$ [kN/m]	1.2	1.2	0.45	1.14	K_{ser} [N/mm]	25000	15750	9357	156213
l [mm]	10000	5800	3600	3600	$s_{\min}$ [mm]	300	110	100	454.5
b_c [mm]	1000	550	600	190.5	$s_{\max}$ [mm]	450	250	200	454.5
h_c [mm]	50	60	50	63.5	b_t [mm]	125	160	38	190.5
f_{cm} [MPa]	30.43	31.24	31.24	17.89	h_t [mm]	500	230	225	88.9
h [mm]	100	120	100	47.6	E_t [GPa]	10	9	8	8.605

The loads g_1, g_2 and $\psi_2 q$ have been applied at the times t_1=14, t_2=35 and t_3=180 days from the concrete pouring for all the composite beams. The time of concrete curing t_s has been assumed as equal to 5 days. The Young's modulus, creep function and shrinkage of concrete have been computed according to the CEB formulas (CEB 1993) by assuming an average environmental relative humidity RH=75%, the mean compressive strength f_{cm} and the notational thickness h specified in Table 1. The area of reinforcement A_s in the concrete slab, considered in the numerical solution, has been neglected in the analytical approach.

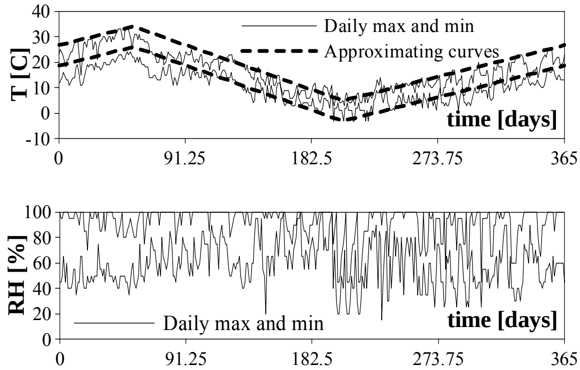

Fig. 5: maximum and minimum daily temperature (top) and relative humidity (bottom) monitored in Florence

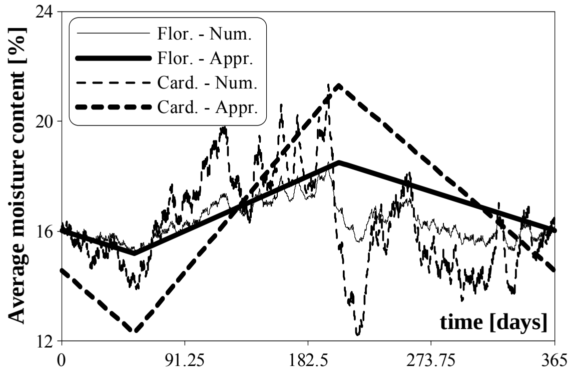

Fig. 6: trend in time of the moisture content averaged over the timber cross-section

All beams have been regarded as exposed to sheltered outdoor conditions (3rd service class according to the EC5, see Ceccotti et al. 2006). The histories of environmental temperature and relative humidity monitored in Florence in the period 9 June 1994 - 8 June 1995 have been assumed in all the analyses. The trends in time of the maximum and minimum daily temperatures are displayed in Fig. 5 (top) including the approximating piecewise-linear curves. The average day-to-night variation is 8 Celsius degrees, while the amplitude of the yearly fluctutation is 29 Celsius degrees. The trends in time of the maximum and minimum daily relative humidities are displayed in Fig. 5 (bottom), with an average daily fluctuation of 34%. The trends in time of the average moisture content over the timber cross-section are displayed in Fig. 6 for the Florence and Cardington beams, together with the approximating piecewise-linear curves. The curves have been obtained using a numerical program which solves the diffusion problem of moisture content over the timber cross-section for the history of environmental relative humidity monitored in Florence and displayed in Fig. 5, on the bottom, as maximum and minimum daily values. The breadth of the timber beam plays a significant role on the amplitude of the yearly moisture content variation: $\Delta u = u_{aver,max} - u_{aver,min} = 3.3\%$ for the Florence beam (b_t=125 mm), and 9% for the Cardington beam (b_t=38 mm), with values closed to those of the Florence beam for the Padua (3%) and Fort Collins (3.8%) beams, respectively.

Fig. 7 displays the numerical and analytical solutions for the Florence beam in terms of mid-span deflection, concrete and timber stresses in the outer fibres, and connector shear force over the support. Fig. 8 displays the mid-span deflections for the other beams. The analytical solutions are obtained using the proposed approach (dashed line) and the current approach (thick solid line). In all the solutions, the Toratti's rheological model has been used. For the sake of clarity, the yearly and daily fluctuations due to environmental variations have been plotted only for the last year. The use of the proposed approach leads to very accurate results in terms of deflections and stresses (see Table 2). Conversely, the current approach markedly underestimates deflection and stresses. The concrete shrinkage, in fact, represents a significant component of the long-term deflection and, as such, should not be neglected. The yearly and daily fluctuations are also important, however not as much as the concrete shrinkage. The proposed method should hence be used for the design of the composite beam in the long-term, especially for an accurate evaluation of the deflection.

When the time of construction is unknown, the entire yearly and daily moisture content

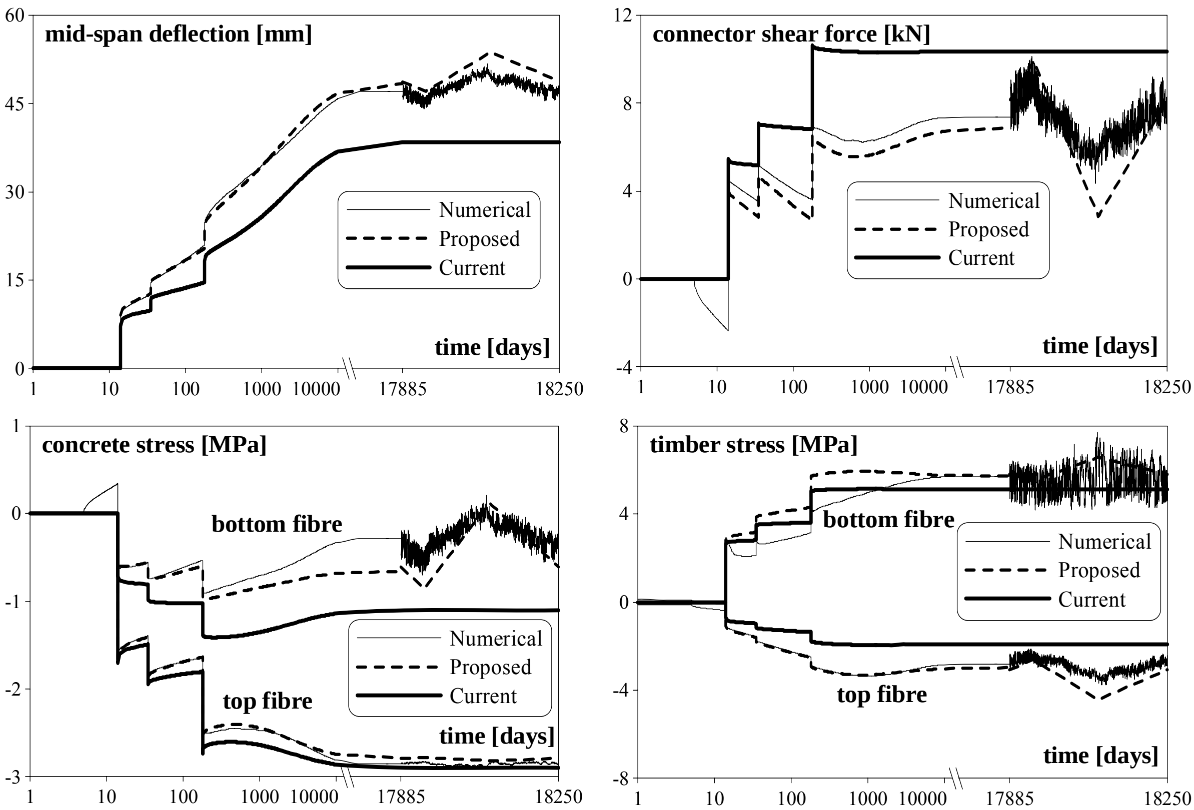

Fig. 7: trends in time of the mid-span deflection (top, left), connector shear force over the support (top, right), outer fibre concrete stresses at mid-span (bottom, left), and outer fibre timber stress at mid-span (bottom, right) for the Florence beam

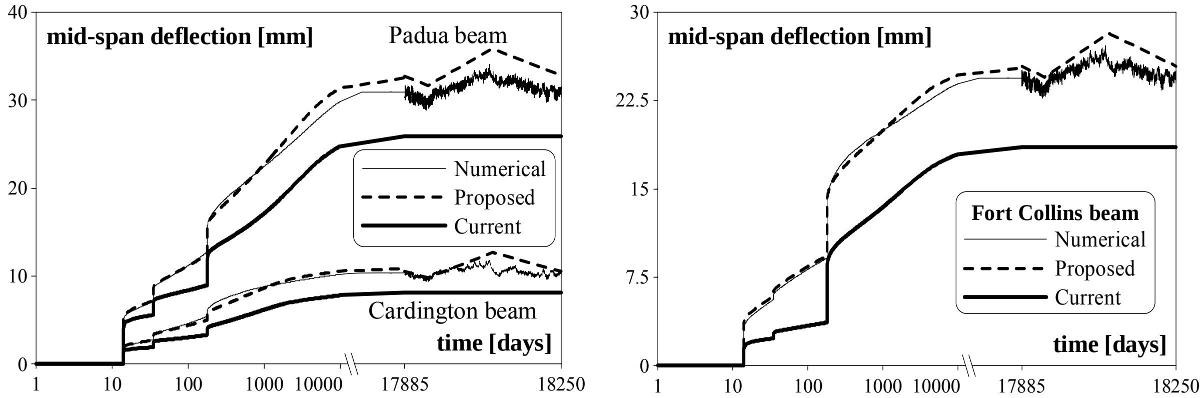

Fig. 8: trend in time of the mid-span deflection for the Padua and Cardington beams (left) and for the Fort Collins beam (right)

Table 2: Percentages of error between numerical and analytical results, as an average on all the beams

	Proposed	Current
Mid-span defl.	5.1	-28.0
Shear force	2.4	7.6
Top fibre concrete stress	3.2	-18.2
Bottom fibre concrete stree	26.3	-39.9
Top fibre timber stress	17.1	-56.9
Bottom fibre timber stress	-14.2	-34.1

Table 3: Differences in percentage between outdoor and diverse indoor conditions, as an average on the Florence and Cardingt. beams

	Δu, ΔT/3	Δu/2, ΔT/3	No Δu, ΔT/3
Mid-span defl.	-4.0	-6.6	-25.3
Shear force	-15.5	-17.3	-33.9
Top fibre concrete stress	-0.2	-0.7	-16.9
Bottom fibre concrete stress	-100.4	-101.6	-106.5
Top fibre timber stress	-11.1	-14.6	-6.8
Bottom fibre timber stress	-1.5	-13.3	-20.9

and temperature variations should be considered in the design of the beam in order to evaluate the most conservative solution:

$$\Delta\varepsilon_y = \alpha_{t,u}(u_{aver,\max} - u_{aver,\min}) + \alpha_{t,T}(T_{y,\max} - T_{y,\min}) - \alpha_{c,T}(T_{y,\max} - T_{y,\min}) \quad (11)$$

$$\Delta\varepsilon_d = \alpha_{t,T} k \Delta T_d - \alpha_{c,T}\Delta T_d \quad (12)$$

Then the yearly $\Delta\varepsilon_y$ and daily $\Delta\varepsilon_d$ environmental variations should be combined with the other loads (dead and live loads $g_1+g_2+\psi_2 q$, shrinkage ε_{cs}) in order to produce the worst effect. For the environmental conditions monitored in Florence, the largest deflection and bending moments in concrete and timber are given by the load combination $S'=g_1+g_2+\psi_2 q+\varepsilon_{cs}-\Delta\varepsilon_y-\Delta\varepsilon_d$, while the largest connector shear force and axial force in timber and concrete are given by the load combination $S''=g_1+g_2+\psi_2 q+\varepsilon_{cs}+\Delta\varepsilon_y+\Delta\varepsilon_d$.

3 Influence of different environmental conditions

The analyses carried out above refer to the case of a TCC exposed to outdoor conditions. Even though the timber beam is protected from direct contact with the rain by the concrete slab, the beam should be assigned to the 3rd service class according to the EC5 (Ceccotti et al. 2006). For TCC's in heated indoor conditions, the environmental variations will be characterised by reduced fluctuations. Some research suggested that in indoor conditions the moisture content variations should be halved with respect to outdoor conditions (Limträhandbok 2001). However, other recent studies (Häglund and Thelandersson 2005) pointed out that the same amplitude of the moisture content variations can be expected in timber beams exposed to outdoor and heated indoor conditions, with a value of about 7 to 10%. In terms of temperature variations, the whole yearly indoor fluctuation including daily variations can be assumed as little as one-third of the environmental fluctuations.

It is then interesting to investigate which differences can be expected in the response of TCC's in indoor conditions (service class 1 and 2 according to EC5) compared to outdoor conditions. The Florence and Cardington beams have been analysed under indoor conditions by assuming one-third of the environmental temperature variations, and the three cases of equal, half and no moisture content variation in each fiber of the timber beam. The outcomes are reported in Table 3 in terms of numerical solutions, and in Figure 9 as analytical solutions using the proposed approach. For the sake of clarity, the yearly fluctuations due to environmental variations have been plotted only for the last year, and the numerical solutions have not been reported being very close one to another.

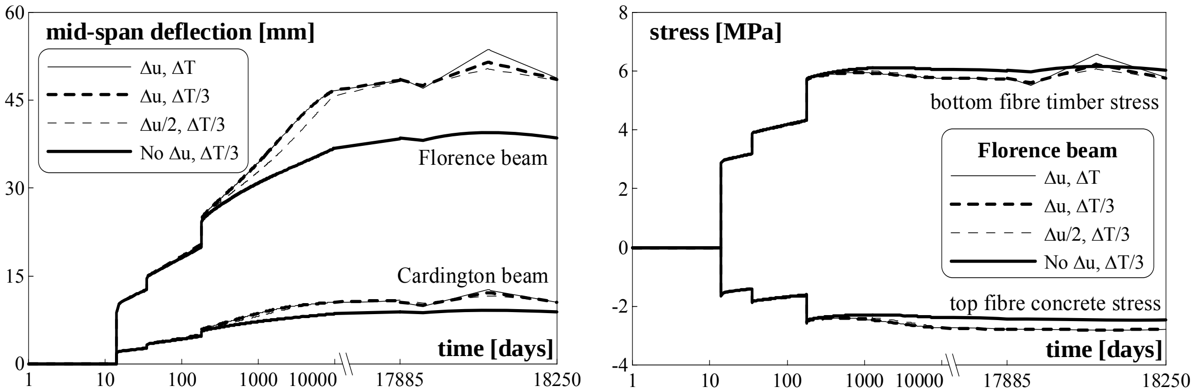

Fig. 9: comparison among the deflections (left) and stresses (right) at mid-span for the Florence and Cardington beams exposed to different environmental conditions

It can be observed that the differences among the solutions in outdoor (Δu, ΔT) and indoor (Δu, $\Delta T/3$, and $\Delta u/2$, $\Delta T/3$) conditions are generally low (max 17%). Those differences are mainly due to the reduced amplitude of the environmental yearly and daily fluctuations, while the long-term effects of the load and concrete shrinkage are hardly affected by the reduction of the yearly moisture content variation from Δu to $\Delta u/2$. This can be justified by the mechano-sorptive effect being almost independent, in the long-term, of the yearly moisture content variations for values of technical interest (Δu>1.65%), as discussed in par. 2.2.1 and depicted in Figs. 1 and 2. A significant difference is observed only when no moisture content variation is considered (Δu=0) where, according to the Toratti's model, the mechano-sorptive effect becomes zero for timber and connection. In this case the creep coefficient of timber and connection approaches the value suggested by the Eurocode 5 for the 2nd service class. The stresses are less affected by the environmental conditions than the deflection. The 100% differences reported in Table 3 refer to very low value of stresses in the concrete, and as such is not representative of a significant variation. This outcome agrees with the evidence that the rheological phenomena mainly affect the deflection of a TCC, while the effect on the stresses is generally limited (Fragiacomo et al. 2006a).

4 Conclusions

The paper investigates the long-term behaviour of timber-concrete composite beams (TCC's). A simplified yet accurate approach based on simple closed form solutions has been proposed for the prediction of all relevant quantities. The approach is an extension of the method suggested by Ceccotti to account for the mechano-soprtive effect, concrete shrinkage, shrinkage/swelling of timber and concrete due to environmental variations, and modality of construction (propped construction). The proposed approach has been compared with the current approximate method and with the numerical solution carried out using a rigorous Finite Element program. The influence of different environmental conditions (outdoor, heated indoor conditions) on the behaviour of the TCC has also been investigated. The primary observations of this research are reported herein after.

1) the Toratti's rheological model, which accounts for the mechano-sorptive effect, is hardly dependent, in the long-term, upon the yearly moisture content variation Δu for values larger than 1.65%.

2) the creep coefficient of connection, assumed by the EC5 twice as large as the creep coefficient of timber, seems to be overestimated according to the outcomes of some tests.

3) the use of the effective modulus method for evaluating the effect on the TCC beam of creep and mechano-sorptive creep leads to accurate results.

4) the effect of concrete shrinkage can be precisely calculated using the rigorous elastic formulas for TCC's with flexible connection, with the inelastic strain due to shrinkage being measured from the time of concrete curing. The creep is taken into account using the effective modulus method, and the influence of the props is negligible.

5) the shrinkage/swelling due to environmental variations can be taken into account using the rigorous elastic formulas for TCC's with flexible connection. The temperature variations in the concrete and timber beams are assumed equal to the environmental one. The moisture content variation in the timber beam is assumed constant in each point and equal to the average value over the cross-section.

6) the numerical-analytical comparison points out that the proposed approach leads to accurate results in terms of deflections and stresses. Conversely, the use of the current approach which neglects concrete shrinkage and shrinkage/swelling due to environmental variations leads to non-conservative and, therefore, unacceptable approximations.

7) the change of environment from outdoor to indoor heated conditions, characterised by one-third of temperature variations and the same or half moisture content variations, leads to minor reductions in deflections and stresses. Some major reductions take place only if no moisture content variations occur at all. However, this case seems more a pure theoretical limit than a real possibility. According to these outcomes, which are based on the use of the Toratti's rheological model, the type of environment (outdoor, or heated indoor) does not seem to play an important role on the performance of the TCC beam. However, since this outcome is strongly dependent on the type of the rheological model used for timber, a confirmation should be searched using other types of rheological models.

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6 Appendix

This Appendix reports the rigorous formulae for elastic analyses of simply supported TCC’s with flexible connection subjected to inelastic strains in the concrete slab and timber beam (Fragiacomo 2006):

$$u_{\max} = u_{\max,full} \cdot \gamma_u \qquad u_{\max,full} = \frac{\Delta\varepsilon_n}{H} \cdot \frac{(EI)_{full} - (EI)_{abs}}{(EI)_{full}} \cdot \frac{l^2}{8} \qquad (13)\ (14)$$

$$\gamma_u = 1 - \frac{8}{(\alpha l)^2} \cdot \left[1 - \frac{1}{\cosh(0.5\alpha l)}\right] \qquad s_f(x) = s_{f,\max,abs} \cdot \gamma_s(x) \qquad (15)\ (16)$$

$$s_{f,\max,abs} = -\Delta\varepsilon_n \cdot \frac{l}{2} \qquad \gamma_s(x) = \frac{1}{0.5\alpha l} \cdot \left[\tanh(0.5\alpha l) \cdot \cosh(\alpha x) - \sinh(\alpha x)\right] \qquad (17)\ (18)$$

$$F(x) = K_{ser} \cdot s_f(x) \qquad N_t(x) = -N_c(x) = N_{t,\max,full} \cdot \gamma_\vartheta(x) \qquad (19)\ (20)$$

$$N_{t,\max,full} = -\frac{\Delta\varepsilon_n}{H} \cdot \frac{(EI)_{full} - (EI)_{abs}}{(EI)_{full}} \cdot \frac{(EI)_{abs}}{H} \qquad M_i(x) = M_{i,\max,full} \cdot \gamma_\vartheta(x) \qquad (21)\ (22)$$

$$M_{i,\max,full} = \frac{\Delta\varepsilon_n}{H} \cdot \frac{(EI)_{full} - (EI)_{abs}}{(EI)_{full}} \cdot E_i I_i \quad \text{with } i = c,t \qquad (23)$$

$$\gamma_\vartheta(x) = 1 + \tanh(0.5\alpha l) \cdot \sinh(\alpha x) - \cosh(\alpha x) \qquad \Delta\varepsilon_n = \Delta\varepsilon_{n,t} - \Delta\varepsilon_{n,c} \qquad (24)\ (25)$$

$$(EI)_{abs} = E_c I_c + E_t I_t \qquad (EI)_{full} = (EI)_{abs} + (EA)^* \cdot H^2 \qquad (26)\ (27)$$

$$(EA)^* = \frac{E_c A_c E_t A_t}{(EI)_{abs}} \qquad \alpha = \sqrt{\frac{K_{ser}}{s_{ef}(EA)^*} \cdot \frac{(EI)_{full}}{(EI)_{abs}}} \qquad (28)\ (29)$$

$$s_{ef} = 0.75 s_{\min} + 0.25 s_{\max} \qquad H = 0.5h_c + t + 0.5h_t \qquad A_i = b_i h_i \qquad (30)\ (31)\ (32)$$

$$I_i = \frac{b_i h_i^3}{12} \qquad \sigma_t = -\sigma_c = \frac{N_t}{A_t} \qquad \sigma_{m,i} = \frac{M_i}{I_i} \cdot \frac{h_i}{2} \quad \text{with } i = c,t \qquad (33)\ (34)\ (35)$$

where:
u, s_f, F, N_i, M_i are the deflection, relative slip between concrete slab and timber beam, connector shear force, axial force and bending moment in the *i* member;
the subscript ‘ max ’ refers to the maximum value of an effect along the beam axis;
the subscripts ‘ *abs* ’ and ‘ *full* ’ refer to the cases of TCC’s with no connection and with rigid connection, respectively;
the subscripts ‘*c*’ and ‘*t*’ refer to the concrete slab and timber beam, respectively;
x is the distance of the cross-section from the support, and l is the beam length;
$\Delta\varepsilon_{n,i}$ is the inelastic strain, uniformly distributed over the cross-section of the *i* member;
K_{ser} is the slip modulus of the connector for serviceability limit state verifications;
E_i, A_i, I_i, b_i, h_i, σ_i, $\sigma_{m,i}$ are the Young’s modulus, cross-sectional area, second moment of area, breadth, depth, stress due to the axial force and stress due to the bending moment in the *i* member, respectively;
t, $s_{\min}$, $s_{\max}$ are the flooring thickness, minimum and maximum connector spacing, respectively.